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Potential impacts of climate change on soil organic carbon and productivity in pastures of south eastern Australia

Rachelle S. Meyer[a,b,*], Brendan R. Cullen[a], Penny H. Whetton[c], Fiona A. Robertson[d], Richard J. Eckard[a]

[a] University of Melbourne, Faculty of Veterinary & Agricultural Sciences, Parkville, VIC 3010, Australia
[b] Australian-German Climate and Energy College, 187 Grattan Street Lab-14, Parkville, VIC 3010, Australia
[c] University of Melbourne, Earth Sciences, Parkville, VIC 3010, Australia
[d] Agriculture Victoria Research Division, 915 Mt Napier Rd, Hamilton, VIC 3300, Australia

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ABSTRACT

Increasing soil organic carbon (SOC) stocks is an often-mentioned option to mitigate greenhouse gas emissions. However, increasing carbon stocks in agricultural soils is difficult and the ability of soils to store carbon as the climate changes is uncertain. This is due to many interacting factors, including those that vary spatially, contributing to organic matter inputs and decomposition rates. We used two models, the Sustainable Grazing Systems whole-farm system model (SGS) and the RothC soil carbon model, to investigate the potential impacts of climate change on SOC stocks in pastures in a temperate, winter-dominant rainfall region of south eastern Australia. A wide range of possible future climates were simulated from 2017 to 2090 at two sites, each with two soil types. Results demonstrate that projected rainfall, the factor with the most variability between climate scenarios, was the primary source of uncertainty in SOC response. Dry climate projections resulted in lower SOC content than other scenarios. The two models were similar in their projected trends, but the RothC model generally gave larger percent changes in soil carbon over the simulation period and a larger range of responses due to changes in site characteristics, particularly clay content. Sustainable stocking rates were determined by the whole-farm system model based on climate, pasture production, and maintaining minimum dry matter coverage. Wet future climates lead to increased production that supported increases in stocking and increases in SOC stocks. While soil carbon accumulated at slower rates or remained steady under dry projections, lower production meant this was accompanied by decreased average 2070–2090 stocking rates, which approached zero by 2090 on the low-rainfall site. This highlights an important interaction between SOC and grazing management. The results demonstrate the extent of the uncertainty associated with soil carbon trading for farmers and the need for adaptation options that allow farms to remain sustainable and productive as the climate changes.

1. Introduction

Increasing soil organic carbon (SOC) has received much attention as a mitigation strategy because of the potential for soil to store substantial amounts of CO_2 from the atmosphere. Examples of global estimates of technical potential include 4.4–11.4 Gt CO_2eq/year for 25 to 50 years (Lal, 2013) and 4.8 Gt CO_2eq/yr for agricultural soil management and restoration (Smith et al., 2013). Despite limitations, such as the reversibility of SOC storage, there have been efforts to develop carbon trading markets using SOC related offset methodologies. Australia has developed national level SOC offset methodologies to meet emission reduction targets under its Emissions Reduction Fund, including the "increase in soil carbon due to conversion from cropping to grazing" methodology (Australian Government Department of the Environment, 2015).

Converting cropping lands to grazing is an option that consistently results in increases in soil carbon (Guo and Gifford, 2002; Lam et al., 2013). It has been estimated that conversion of cropping lands in Victoria to a crop - pasture rotation and stubble retention could result in carbon accumulation of up to 4.5 Mt. CO_2eq/year, 3.7% of Victoria's emissions (Robertson and Nash, 2013). Overgrazing typically results in lower soil carbon levels than observed under more moderate stocking

* Corresponding author at: University of Melbourne, Faculty of Veterinary & Agricultural Sciences, Parkville, VIC 3010, Australia.
E-mail addresses: meyer.r@unimelb.edu.au (R.S. Meyer), bcullen@unimelb.edu.au (B.R. Cullen), Robertson@ecodev.vic.gov.au (F.A. Robertson), rjeckard@unimelb.edu.au (R.J. Eckard).

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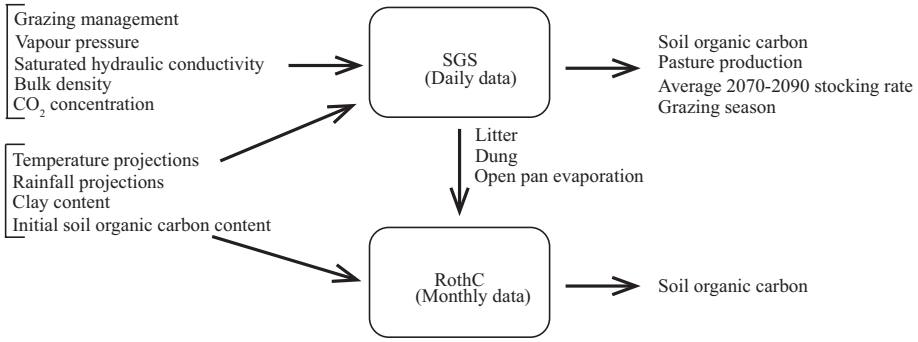

Fig. 1. The methodolgical framework of the analysis showing the use of two models, the unique and overlapping inputs into the models, the RothC inputs obtained from SGS, and the outputs used.

rates (Conant et al., 2001; Liu et al., 2016; Soussana et al., 2010). The impacts of climate change on the potential of converting cropping to grazing lands as a mitigation option, and the stocking rates required to achieve soil carbon accumulation in future climates has not been investigated.

Both the carbon inputs and the outflows will be affected by changes in temperature, rainfall and CO_2 concentration in direct and indirect ways that vary based on the current conditions at a site and the expected changes in climate (Baldock et al., 2012; Gottschalk et al., 2012). In some locations temperature increases will increase pasture productivity, increasing SOC inputs (Cheng et al., 2011; Lu et al., 2013). In other regions, and for sensitive species, comparatively small increases in temperature can reduce plant productivity (Cullen et al., 2012; O'Leary et al., 2011; Wang et al., 2016). Higher amounts of rainfall have been shown to increase SOC primarily due to increased plant productivity (Falloon et al., 2007; Hobley et al., 2015; Shen et al., 2009). Increases in atmospheric carbon dioxide (CO_2) concentrations increase plant productivity in locations where water and nutrients are not limiting (Ainsworth and Long, 2005; Cao and Woodward, 1998; Runion et al., 2009).

The impacts of climate change on carbon outflow from soils are less well understood. Moist soils have higher respiration rates than dry soils (Baldock et al., 2012; Condron et al., 2014; Shen et al., 2009). Increases in temperatures increase soil respiration (Cheng et al., 2011; He et al., 2012; Shen et al., 2009) with the largest impact on cool soils (Kirschbaum, 1995) and areas with high SOC stocks (Crowther et al., 2016). However, the sensitivity of this response is debated, and several uncertainties remain (Bradford et al., 2016; Davidson and Janssens, 2006). Relationships between soil respiration and CO_2 concentration have also been documented (De Graaff et al., 2006; van Groenigen et al., 2014). It is possible that increased carbon inputs from increased plant productivity under elevated CO_2 increase microbial activity and therefore SOC turnover (Kuzyakov, 2011; van Groenigen et al., 2014). The implications of this priming effect are uncertain but could have long-term consequences on SOC turnover.

The net impact of these processes needs to be determined for particular areas (Gottschalk et al., 2012) and management options. If national mitigation policies are going to include increases in SOC, the potential of these offset methodologies to increase, or even maintain, carbon as the climate changes is integral information. Given that one of the most consistent and documented ways to increase SOC in soils is through conversion from cropping to pasture (Lam et al., 2013; Liu et al., 2016; Robertson and Nash, 2013) and that this is already an Australian Emissions Reduction Fund (ERF) offset methodology, we modelled the impacts of climate change on carbon stocks in Australian soils under pasture. We also addressed major sources of uncertainty in the potential response of SOC to climate change, namely climate projection uncertainty, both that from climate models and emissions scenarios, and uncertainty inherent in process-based soil carbon modelling.

2. Materials and methods

RothC version 26.3 in Microsoft Excel format (Coleman and Jenkinson, 2014) and the Sustainable Grazing Systems whole-farm system model (SGS) (version 5.2.15) (Johnson, 2013) were used to investigate the impacts of a wide range of future climate projections on SOC at two grazed pasture sites in south-eastern Australia. Sites were modelled with both high and low initial carbon contents, which were based on values from long-term pasture and long-termed cropped sites, respectively. The low carbon soils are simulated to investigate the climate impacts on soil carbon accumulation following a switch from cropping to pasture, while the high carbon scenarios address climate impacts on soils closer to equilibrium. Livestock were removed at low dry matter coverage to prevent overgrazing. Two models were used to address some of the SOC modelling uncertainty associated with projecting impacts of climate change on SOC stocks. Both models require inputs for climate and soil characteristics. The same temperature and rainfall data generated for the climate projections were used in both models. RothC uses average monthly temperature, while SGS uses daily minimum and maximum temperatures. SGS also requires vapour pressure and solar radiation, while RothC requires open-pan evaporation. To ensure consistency between the two model simulations, dung inputs and litter requirements of RothC were obtained from SGS outputs for the same scenario. The general framework of the methodology is shown in Fig. 1.

In the SGS model plant growth and grazing processes are integrally connected with the SOC and nitrogen cycles (Johnson et al., 2003). Indirect impacts of climate and atmospheric CO_2 concentrations on pasture and root growth, and consequently SOC inputs, are also included. The SGS model includes a simple carbon model with three pools: fast turnover, slow turnover, and inert carbon. The SGS model has been validated for pasture production (Cullen et al., 2008; White et al., 2008) and soil water content (Lodge and Johnson, 2008) in Australia, with the soil organic matter routines published in Meyer et al. (2015).

The RothC soil carbon model is more complex than the soil carbon routine in the SGS model, with carbon transfers between several conceptual soil organic matter pools, including decomposable plant material (DPM), resistant plant material (RPM), fast and slow microbial biomass, humified organic matter (HUM) and inert organic matter (IOM). RothC has been used extensively to model the impacts of climate and management on SOC stocks (Gottschalk et al., 2012; Robertson and Nash, 2013; Smith et al., 2007) and has been validated for Australian sites (Skjemstad et al., 2004). Direct climate impacts on organic matter turnover, specifically temperature and soil water status, are incorporated in both SGS (Johnson (2003)) and RothC (Coleman et al., 1997). The decomposability of organic inputs is a function of plant digestibility in SGS (Johnson, 2013) while a default value for improved grassland is used in RothC (Coleman and Jenkinson, 2014). The impact of low ground-cover on soil processes and the role of clay in influencing

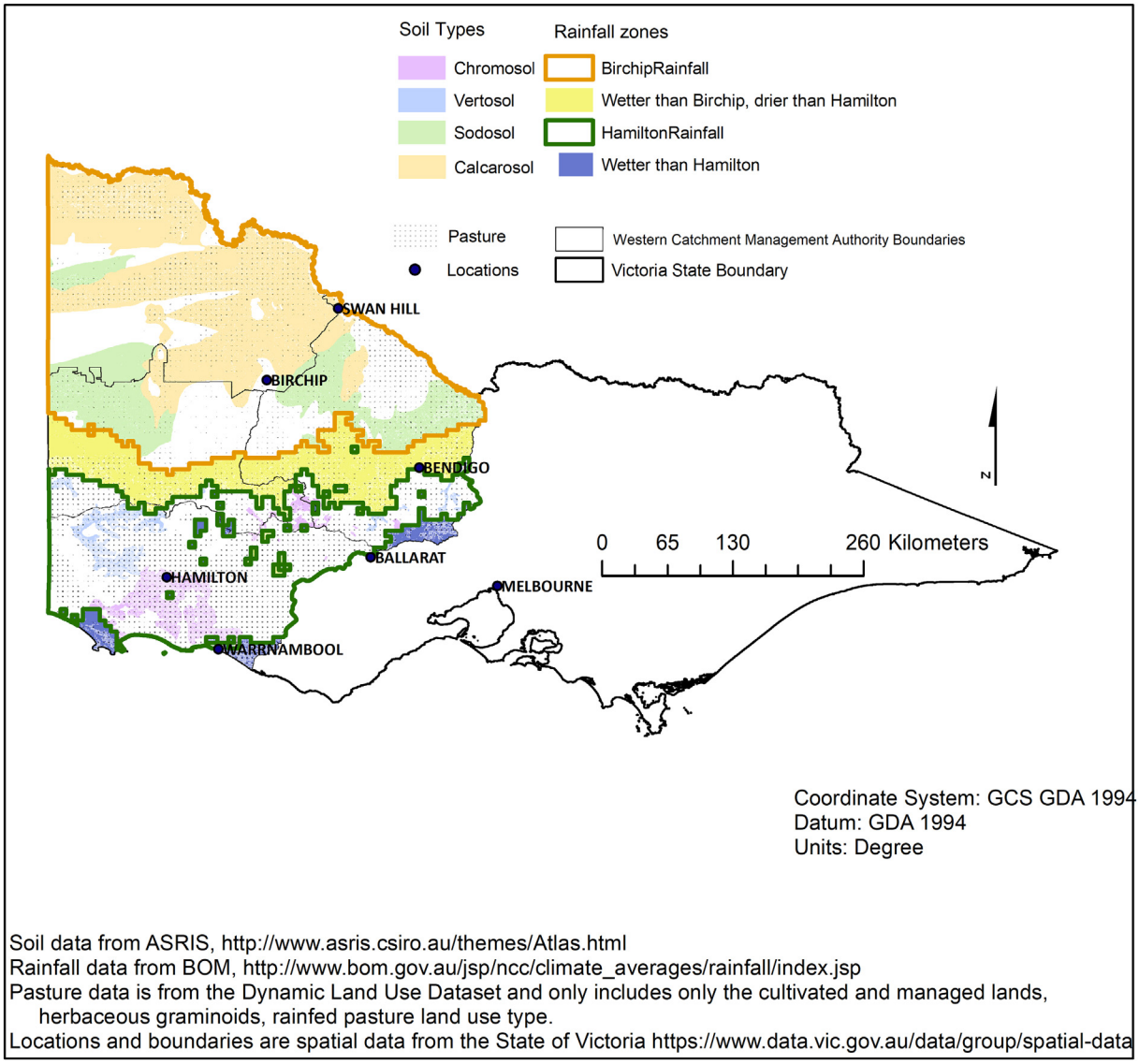

Fig. 2. Areas of western Victoria with similar soil types and rainfall (± 1 SD) as that of the modelled sites. Data layers used to create this map: Bureau of Meteorology (2016) rainfall averages (1961–1990), soil data from ASRIS (Ashton and McKenzie, 2001; ASRIS, 2011), rain-fed pasture area from the Dynamic Land Use Dataset (Geoscience Australia, 2010) and boundaries and locations from the State of Victoria Spatial Dataset (State of Victoria Department of Environment Land Water and Planning, 2018a, b, c).

organic matter turnover also differ between the two models. Comparisons in the structure between these two and other models are available (Moore et al., 2014; Smith et al., 1997). Both models assume that historic relationships between SOC turnover and temperature or rainfall will remain the same as the climate changes and CO_2 concentrations increase.

2.1. Design and model parameterisation

Impacts of climate change from 2017 to 2090 were modelled on two sites each with two soil types. A high-rainfall site with a historic (1901–2011) annual average rainfall of 676 mm was modelled based on data from Hamilton, Victoria (37°45′S and 142°0′E). The high-rainfall site was modelled with soil types representative of a Chromosol and a Vertosol. The low- rainfall site (average 355 mm) was modelled based on data from Birchip, Victoria (35°55′S and 142°51′E) with soil types representative of a Calcarosol and a Sodosol. These soil types and rainfall represent much of pasture land in western Victoria (Fig. 2).

The high-rainfall site was modelled with perennial ryegrass (*Lolium perenne*), phalaris (*Phalaris aquatica*), and subterranean clover (*Trifolium subterraneum*), and the low-rainfall site was modelled with annual ryegrass (*L. multiflorum*) and subterranean clover. Rooting depths were 40 cm for the ryegrass species, 50 cm for subterranean clover, and 120 cm for phalaris. These depths have been validated for these species in SGS (White et al., 2008) and represent > 90% of the SOC deposition zone for these species (Crush et al., 2005). A full description of the sites and parameters are given in Meyer et al. (2015). Key model parameters and the publications they were derived from are included in Table 1.

Each soil type was modelled with both a high initial SOC content and a low initial SOC content to a depth of 30 cm. The high amount of SOC is representative of that managed as long-term pasture sites. Low SOC values are similar to those managed as long-term cropping areas, transitioning to permanent pasture. The initial soil carbon values are based on data from sites near Hamilton and Birchip (see Table 1) available from Victorian Resources Online (2008, 2009), Skjemstad and Spouncer (2003) and summarized in Robertson and Nash (2013). Due to a lack of specific data on long-term pasture in the Birchip region the

Table 1
Parameter values for soil characteristics used in the SGS model, and in the case of clay and total soil organic carbon, the RothC model. The literature on which these were based is included in footnotes. A more detailed description of parameterisation of these sites is available in Meyer et al. (2015).

Soil Type	Carbon status	Bulk density (g/cm3)	Clay content (%)	Saturated hydraulic conductivity (cm/day)	Plant Available Water Holding Capacity to 40 cm* (mm)[a]	Total Soil Organic Carbon (0–30 cm, t/ha)[b]	Fast pool organic carbon content (0–30 cm, t/ha)[e,f]	Slow pool organic carbon content (0–30 cm, t/ha)[e,f]
High rainfall[c,e]								
Chromosol[e]	High carbon	1.24	25	to 15 cm: 6.2 15–30 cm: 6.7	56.5	88.0	15.8	62.5
	Low carbon				53.5	52.0	9.4	36.9
Vertosol	High carbon	1.25	40	to 70 cm: 5.0	60.5	108.0	19.4	76.7
	Low carbon				59.0	74.0	13.3	52.5
Low rainfall[d,f]								
Sodosol[a]	High carbon	1.37	20	to 30 cm: 21.0	30.0	47.5	9.6	35.2
	Low carbon				25.0	21.2	6.4	10.5
Calcarosol	High carbon	1.37	30	to 15 cm: 6.2 15–30 cm: 6.7	72.5	62.0	10.1	45.5
	Low carbon				69.5	32.0	9.6	16.0

[a] Values for the Sodosol PAWHC are to 20 cm, since rooting depth is limited to that depth due to a saline layer.
[b] Robertson and Nash (2013) source used for initial total SOC concentration.
[c] Victorian Resources Online (2008) source for most high-rainfall soils' hydrology parameters.
[d] Victorian Resources Online (2009) source for low-rainfall soils' hydrology parameters.
[e] Graham et al. (2005) source for some Chromosol hydrology parameters and high-rainfall initial SOC fractions.
[f] Baldock et al. (2013a) source for low-rainfall initial SOC fractions.

initial high SOC content was set to the 50% equilibrium value for these soils in SGS. Sites with low initial SOC also have a reduced plant available water holding capacity; determined based on a relationship published by Baldock (2009), in which a given increase in SOC content increases soil water holding capacity to a greater extent in low-clay soils than high-clay soils. The expected change in PAWHC (mm) with a 1% increase in SOC (y) for soils with a given clay content (x) is $y = -0.1229x + 5.5029$. Parameters for soil organic matter dynamics were the same on all soils in SGS, with reference decay rates, adjusted by temperature and soil water content, of 0.18%/day in the labile pool, 0.004%/day in the slow pool, and a transfer from the slow pool to the fast pool in 30% clay of 0.03%/day. These values were determined during calibration of the model using long-term experimental data from Hamilton (Graham et al., 2005), as described in Meyer et al. (2015).

Livestock management was set to prevent overgrazing, so as not to confound the impacts of climate change with overgrazing. Pastures were grazed until dry matter reached 0.8 t/ha and were restocked when dry matter reached 1.3 t/ha. In the study region, dry matter generally falls below this threshold due to a lack of rainfall. On the high-rainfall site the stocking density imposed when grazing occurred was 29 mature wethers/ha and on the low-rainfall site it was 10 mature wethers/ha. Average 2070–2090 stocking rates for a given site and climate scenario were calculated as the average of the daily stocking rates from 1/01/2070 to 31/12/2090. Average 2070–2090 stocking rates give an indication the sustainable stocking rate at the end of the simulation for a specific scenario. Median grazing season refers to the period in which pastures supported grazing each year between 2070 and 2090, starting on the median date grazing began and lasting until the median day grazing ended. To further investigate the role of stocking management in buffering impacts on SOC we implemented the average 2070–2090 stocking rate from the scenario without climate change every day of the year in an 8.5 RCP hot and dry climate. This scenario is referred to as the fixed scenario, since the stocking rate is constant regardless of dry matter availability.

Clay and the total initial SOC contents were the same in SGS and RothC (Table 1), while defaults were used for other soil factors in RothC. This parameterisation was designed to keep individual scenario inputs into the models as similar as possible, without overfitting RothC to the SGS specifications described above. SGS SOC pools were split among the RothC carbon pools. The SGS slow carbon pool is equivalent to the RothC HUM pool and the SGS inert pool is identical to the RothC IOM pool (Moore et al., 2014). The SGS labile or fast carbon pool was split among the remaining RothC carbon pools with the majority (84%) in the RPM, which is equivalent to particulate organic matter, 10% in the fast biomass, and the remainder in the DPM and slow biomass pools. The initial allocation of carbon into the DPM and biomass pools does not have a material impact after the first year of the simulation (Skjemstad et al., 2004).

RothC requires monthly carbon inputs, including plant residues and dung carbon. To ensure consistency between the two models, these values were obtained from SGS outputs from each scenario (Fig. 1). SGS litter in tonnes of dry matter was converted to tonnes of carbon with a factor of 0.43, and SGS calculates daily outputs of dung C. In RothC, it was assumed that soil was 'bare' when average monthly dry matter was < 0.4 t/ha, reflecting low ground cover at low pasture mass (Lodge and Murphy, 2002). In RothC, carbon turnover is faster in bare soil compared to vegetated soil.

2.2. Climate projection inputs

To develop climate change projections for the 2017–2090 period we used a change factor approach, where change factors associated with a given climate scenario for each site and season (winter growing season v. summer) over the simulation period were applied to the detrended historic climate. Change factors were obtained from SimCLIM 2013 AR5 software (version 2.1) for Hamilton and Birchip (Warrick, 2007).

Table 2
Rainfall change factors (%) for the median, 10th and 90th percentile GCMs, applied to historic rainfall data for RCP 4.5 and 8.5 at both the high- and low-rainfall sites, for the years 2030, 2050, 2070 and 2090.

Emissions Scenario	Climate scenario (GCM)	Season	2030	2050	2070	2090
High-rainfall site						
4.5 RCP	10th	Oct-April	−11.4%	−17.5%	−22.0%	−24.0%
	percentile	May-Sept	−9.5%	−14.6%	−18.3%	−20.0%
	median	Oct-April	−2.6%	−4.0%	−5.0%	−5.5%
		May-Sept	−2.8%	−4.3%	−5.4%	−5.9%
	90th	Oct-April	9.0%	13.8%	17.4%	19.0%
	percentile	May-Sept	3.9%	5.9%	7.4%	8.1%
8.5 RCP	10th	Oct-April	−13.1%	−23.8%	−36.7%	−50.5%
	percentile	May-Sept	−10.9%	−19.8%	−30.6%	−42.1%
	median	Oct-April	−3.0%	−5.4%	−8.3%	−11.5%
		May-Sept	−3.2%	−5.9%	−9.1%	−12.5%
	90th	Oct-April	10.3%	18.8%	29.0%	39.9%
	percentile	May-Sept	4.4%	8.0%	12.3%	17.0%
Low-rainfall site						
4.5 RCP	10th	Oct-April	−11.6%	−17.8%	−22.3%	−24.4%
	percentile	May-Sept	−12.8%	−19.6%	−24.7%	−27.0%
	median	Oct-April	−0.8%	−1.3%	−1.6%	−1.7%
		May-Sept	−3.3%	−5.0%	−6.3%	−6.9%
	90th	Oct-April	13.9%	21.2%	26.6%	29.1%
	percentile	May-Sept	4.7%	7.2%	9.1%	9.9%
8.5 RCP	10th	Oct-April	−13.3%	−24.1%	−37.3%	−51.3%
	percentile	May-Sept	−14.6%	−26.7%	−41.2%	−56.6%
	median	Oct-April	−0.9%	−1.7%	−2.7%	−3.7%
		May-Sept	−3.7%	−6.8%	−10.5%	−14.4%
	90th	Oct-April	15.8%	28.8%	44.5%	61.2%
	percentile	May-Sept	5.4%	9.8%	15.1%	20.8%

2.2.1. Ensemble model selection

All 40 of the Global Circulation Models (GCM) from the coupled model intercomparison (CMIP 5) that are available in SimCLIM were included in the ensemble used to generate the climate projections. Of the 40 models, the models that produced the 10th percentile, median, and 90th percentile temperature (GCMt) and rainfall (GCMr) projections were used to develop several scenarios. This captures most of the climate model variability and sets reasonable bounds on possible responses of soil carbon stocks to climate change. These projections reflect the variability in the 40 GCMs and are not meant to be interpreted as replicating the future distribution of rainfall or temperature.

2.2.2. Future climate scenarios

In addition to a scenario without climate change, five future climate scenarios were constructed for both an intermediate emissions scenario, the 4.5 Representative Concentration Pathway (RCP), and a high emissions scenario (8.5 RCP) at both sites. These five scenarios were:

- hot and dry: 90th percentile GCMt (GCMt90) and 10th percentile GCMr (GCMr10)
- warm and dry: 10th percentile GCMt (GCMt10) and GCMr10
- intermediate: the median GCMt and median GCMr
- hot and wet: GCMt90 and 90th percentile GCMr (GCMr90)
- warm and wet: GCMt10 and GCMr90

Hot (GCMt90) and warm (GCMt10) are used to refer to temperature projections and wet (GCMr90) and dry (GCMr10) are used to refer to precipitation projections throughout this paper; for instance, when referring to the effects of rainfall regardless of temperature. Mixing of GCMs for temperature and rainfall may not always be appropriate since one model may make assumptions that mean the other is less likely to occur. However, on coastal sites similar to our high-rainfall site, temperature and rainfall projections are only loosely correlated ($r = -0.11$) (Watterson, 2012). In the interior region where the low-rainfall site is located, temperature and rainfall are negatively correlated ($r = -0.6$) suggesting that matching hot and dry scenarios is a reasonable assumption (Watterson, 2012). The limitations of the warm and dry and hot and wet scenarios on the low-rainfall site are addressed in the discussion.

2.2.3. Generating climate temperature projections

Climate projections from 2017 to 2090 were generated by applying change factors to historic data, detrended for historic climate change effects. Daily climate data from Birchip and Hamilton from 1940 to 2015, obtained from a SILO patch point dataset (Jeffrey et al., 2001), were tested for significant trends in monthly minimum and maximum temperature using a *t*-test or Mann-Kendell test depending on the distribution of the data. For June and August maximum temperature at Birchip and September minimum and maximum temperature at Hamilton the modified Mann-Kendall test was used due to statistically significant autocorrelation. Change factors in SimCLIM have a baseline year of 1990, so data were detrended and anchored to 1990 using the formula:

$$\text{Observed} + (\text{TrendMonth}^{\circ}\text{C/year} * (1990 - \text{year}))$$

Temperatures before 1990 were increased and those after 1990 were decreased based on the historic trend calculated in the previous step. In months without a significant temperature trend, change factors were applied to the historic data (i.e. TrendMonth = 0). Given the inherent variability present in rainfall data, these were not detrended. The climate change factors for the various climate scenarios were applied to the detrended historical time series, which is referred to as the scenario without climate change. A random 'shuffle' of the detrended baseline data was created to investigate the importance of sequence of the years and to address the impact of natural variability. The shuffle was created from the detrended baseline with April to March years reordered randomly. April to March years were used to conserve El Nino patterns through the annual cycle.

Change factors for minimum temperature, maximum temperature, and rainfall for each scenario were determined for six-month periods. This was to allow for differences in projections for the wet cool season (May-Sept), referred to as the winter growing season, and the dry and warm summer (Oct-April). This also allowed for reasonably consistent model selection over the course of the year, with at most two models (i.e. one for the cool/wet and one for the warm/dry season) used. This means for each climate variable there are different change factors for 3 climate models (the 10th percentile, median, and 90th percentile GCM), 2 emissions scenarios (4.5 RCP and 8.5 RCP), 2 seasons (winter growing season and summer) and 2 sites (high rainfall and low rainfall). These projections were then used to construct the previously described climate scenarios, with change factors for summer applied to October to April and those for the winter-growing season applied to May to September. Table 2 provides a selection of change factors applied to the historic data to construct the various rainfall projections.

SGS also requires vapour pressure and solar radiation as inputs. Solar radiation was kept the same as that in the historic data. Although solar radiation may increase over the simulation period, projected changes are generally < 5%. Exceptions are the potential for increases of up to about 10% in winter under a high emissions scenario in this region (CSIRO and Bureau of Meteorology, 2015). These sunnier conditions would result in somewhat drier winters late in the high emissions simulations compared to what we have projected. In contrast, vapour pressure was estimated using Teten's formula (Johnson, 2013), in which the minimum projected temperature influenced the vapour pressure:

$$\text{VapPress (hPa)} = 6.11 * \text{EXP}((17.5 * \text{ProjMinT})/(\text{ProjMinT} + 241))$$

This reflects that saturated vapour pressure is a function of projected minimum temperature (ProjMinT) and allows vapour pressure to change with increases in minimum temperature over the course of the simulations. RothC requires open pan evaporation which was estimated

by using the climate projections to estimate potential evapotranspiration using the standard FAO technique (Smith, 1992). The estimate of potential evapotranspiration was converted to open pan evaporation based on conversion factors calculated from the historic data. The conversion factors were site and month specific.

The impact of increased CO_2 on plant productivity was included using the CO_2 pathways to 2100 of Meinshausen et al. (2011) for the 4.5 and 8.5 RCPs, which result in CO_2 concentrations of 534 and 845 ppm in 2090, respectively. Scenarios without climate change were modelled with constant CO_2 concentrations of 380 ppm.

2.3. Analysis of model outputs

The outputs presented focus on SOC and productivity under the various scenarios. The trends in SOC over the simulation period are shown as the annual average SOC (t/ha, 0–30 cm). Change in pasture production, as the annual sum of daily pasture growth in kg DM/ha, and average 2070–2090 stocking rate are summarized as the percentage difference between a given scenario and the scenario without climate change for the same site and soil type. These differences were calculated for the end of the simulation period (2070 to 2090) to show the long-term impacts of the various climate scenarios. Percentage change is informative in this case, given that small absolute changes at the low-rainfall site have a much larger impact than the same change at the high-rainfall site. The median grazing season from 2070 to 2090 demonstrates how the various climate scenarios impact the timing and length of the grazing season. Pasture utilisation, calculated as the total annual intake divided by the total annual growth, was calculated to explore differences in response of pasture production and stocking to climate, but is not reported for every scenario.

Correlations between climate inputs and the change in SOC, as percentage of initial soil carbon stock, were performed to investigate which climate inputs were most strongly associated with soil carbon output and how this varied between the models and soil types. This serves as a basic sensitivity analysis and allows for some discussion of model processes behind the observed responses to climate change.

3. Results

3.1. Climate projections

Ten climate scenarios (5 scenarios by 2 RCPs) for each site, in addition to the scenario without climate change, were generated and cover a broad range of potential future climates. The complete range in projected maximum temperature and rainfall for both sites, using the 10% and 90% GCMs, are shown in Fig. 3. Several climate scenarios within this range were modelled but are not included in Fig. 3. Increases in maximum temperature by 2090 range from 0.75 °C above 1990 levels in low-emissions (4.5 RCP), warm (GCMt10) scenarios at the high-rainfall site to 5.2 °C above 1990 levels in high-emissions (8.5 RCP) hot (GCMt90) scenarios at the low-rainfall site. The driest and wettest scenarios both occur in the 8.5 RCP scenarios. At the low-rainfall site, the driest GCMs (GCMr10) result in reductions in rainfall of 57.5% during the winter growing season (predicted 2080–90 May to September median = 77 mm), while increases in rainfall of 62.1% occur with GCMr90 during the summer (predicted 2080–2090 October to April median = 215 mm). The historic (1898–1995) median rainfall at this site is 175.9 mm during winter growing season and 121.1 mm in the summer (Australian Government Bureau of Meteorology, 2018). All wet scenarios (GCMr90) had increased rainfall year-round, with greater increases in the summer than the winter growing season. The differences between the seasons were not as distinct for projections resulting in rainfall declines (Table 2).

3.2. Model outputs

The trends in SOC simulated by RothC and SGS were similar. Although RothC generally gave greater changes in soil carbon over the simulation period, both models lead to the same conclusions, with uncertainty in projected rainfall the largest source of variability in future SOC stocks (Fig. 4). Analysis of a random shuffle of the detrended time series gave similar results (data not shown) suggesting that the role of natural variability in SOC response was small compared to projected climate change. Across sites and models, the dry scenarios (GCMr10) had equal or lower 2090 SOC amounts than the scenario without climate change. In some dry scenarios, particularly on soils with high initial SOC on the low-rainfall site, SOC stabilised for several years and then began to slowly decline (Fig. 4). In wet scenarios (GCMr90) SOC increased more quickly over the simulation period compared to the scenario without climate change (Fig. 4a,b,c). A notable exception to similar trends between models occurred on the high SOC Vertosol when using RothC, where SOC stocks did not diverge across climate scenarios (Fig. 4d). RothC also gave consistently larger changes in SOC over the simulation period compared to SGS. The absolute and percent change in the simulated SOC for the various scenarios and both models is included in the Supplementary material.

The wide range of rainfall projections have a more pronounced impact on SOC than other factors, including temperature and emission scenario (Fig. 4a,b,c). However, emission scenario did have noticeable impacts, with SOC stocks higher in dry 4.5 RCP scenarios than dry 8.5 RCP scenarios, particularly on the low-rainfall site. In most cases, the range of uncertainty in the simulated SOC response using 4.5 RCPs is considerably less than that associated with 8.5 RCPs.

Declines in rainfall were associated with decreases in pasture production (Fig. 5). Dry 8.5 RCP scenarios resulted in declines in pasture production of 16–72% compared to the scenario without climate change. Wet 8.5 RCP scenarios resulted in increases in pasture production of 38–63% compared to the scenario without climate change. Average 2070–2090 stocking rate responses followed the same trends as pasture production (Fig. 6). However, in the case of the median climate scenarios, pasture production increased up to 24% and SOC stocks increased, despite the slight decline in rainfall.

Grazing implementation in SGS also influenced the modelled outputs. Stock were removed when dry matter reached 0.8 t/ha and were returned when dry matter reached 1.3 t/ha (i.e. a put and take system). Soil organic carbon response to dry and median climate scenarios, and the associated reduction in pasture production, was buffered through moderate to large reductions in average 2070–2090 stocking rate. Reductions were particularly large on the low- rainfall site under dry 8.5 RCP scenarios (Fig. 6). The relatively small increases or maintenance of initial SOC amounts observed in the dry 8.5 RCP scenarios on the low-rainfall site occurred while pasture production declined 53–72% and average 2070–2090 stocking rate was effectively reduced by 70%–90% compared to the scenario without climate change. In the case of wet 8.5 RCP scenarios, the increases in SOC observed were concurrent with increases in pasture production of 38–63% and increases in the average 2070–2090 stocking rate of 16–50%.

A lower proportion of the pasture grown was used by stock on the low-rainfall site than the high-rainfall site and in dry scenarios compared to median and wet scenarios. For example, on the high-carbon Vertosol on the high-rainfall site, the 2070–2090 median pasture utilisation ranged from 52% to 58% in the wet scenarios and the scenario without climate change but was only 23% in the hot and dry scenario. On the high-carbon Calcarosol on the low-rainfall site, the 2070–2090 median pasture utilisation was 15% in the scenario without climate change, 21% in 8.5 RCP hot and wet climate scenario and only 3% in the 8.5 RCP hot and dry climate.

The results of the fixed grazing scenarios, in which the average 2070–2090 stocking rate for the scenario without climate change is implemented every day in the 8.5 RCP hot and dry climate, are included

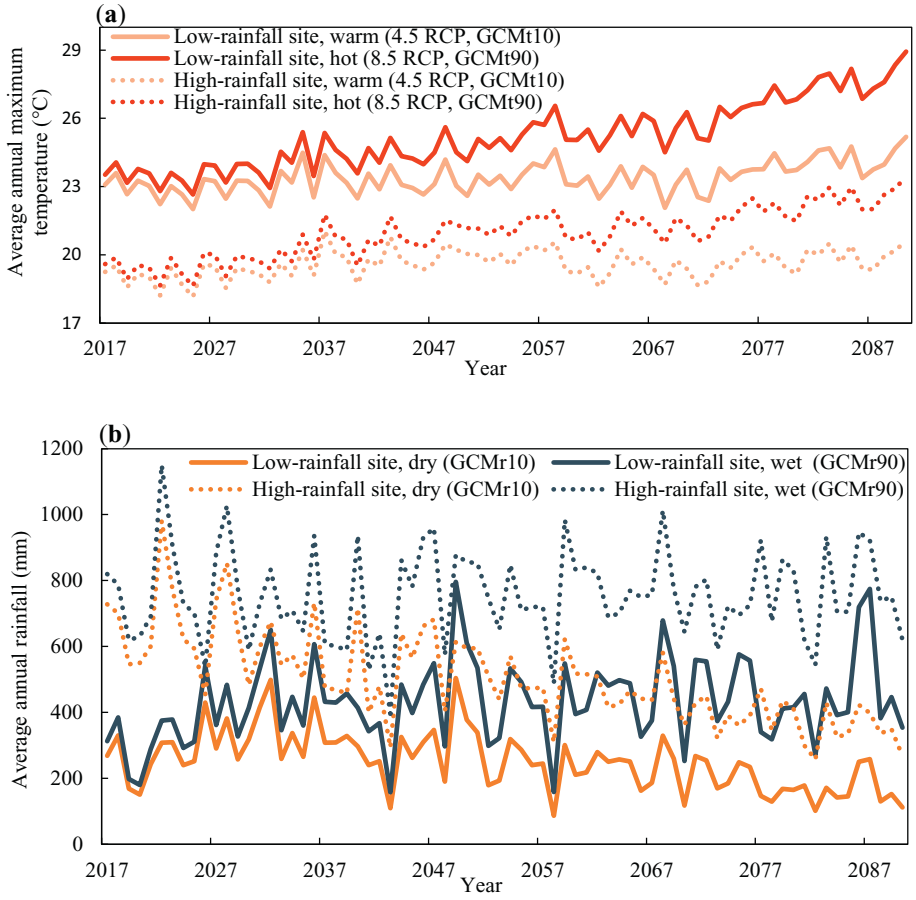

Fig. 3. Future projections with the least and most change in average annual maximum temperature (a) and largest decreases and increases in annual rainfall (b) for the high- and low-rainfall sites. All rainfall projections shown use an 8.5 RCP. Refer to legends for GCM and emissions scenarios.

in Fig. 4 (purple lines). These results show the greater impact of this unresponsive grazing strategy on high-rainfall sites and in the RothC simulations. For instance, in all but one scenario (Vertosol modelled with SGS) high-SOC soils become a net carbon source by the end of the simulation period under unresponsive grazing management. In low SOC soils, SOC at the end of the simulation period was from 3 t C/ha (Sodosol) to 29 t C /ha (Chromosol) lower than would be expected under the hot and dry scenario with stocking that is responsive to dry matter coverage.

The change in average 2070–2090 stocking rate was associated with a change in median grazing season duration. At the low-rainfall site the dry 8.5 RCP scenarios were severe enough to result in no grazing in the 2070–2090 median grazing season, while the median grazing season in the scenario without climate change began in July and ended in November (results not shown). On the high-rainfall site the 2070–2090 median grazing season was shortened by about 2 months in dry 8.5 RCP scenarios while in wet scenarios grazing began earlier and continued for approximately 10 months (Fig. 7).

The association between the modelled SOC output from 2070 to 2090 (as % initial SOC) and the annual rainfall input was highly significant ($P < 0.001$) in every scenario and using both models (see Supplementary material). Annual rainfall accounted for the most variation in the change in SOC on the chromosol and the least on the vertosol. The amount of change in SOC associated with a given change in annual rainfall (effect size) was similar in the two models on the sodosol, chromosol, and calcarosol, with the RothC effect size 2%, 11–12%, and 9–16% larger than the SGS effect size in these soil types, respectively. On the vertosol the effect size was greater when using SGS, with the SGS effect size 89.5% larger than the RothC effect size on the low-carbon vertosol and more than twice the RothC effect size on the high-carbon vertosol (see Supplementary material).

The association between the amount of SOC from 2070 to 2090 (as % initial SOC) and average minimum winter growing-season temperature was variable with positive correlations significant ($P < 0.007$) in low carbon soils on the high-rainfall site and negative correlations significant on the low-rainfall site when using RothC ($P < 0.0014$), except for the low-carbon calcarosol ($P = 0.08$). Less variation in the change in SOC was attributable to temperature compared to rainfall (see Supplementary material).

4. Discussion

With both models, SOC exhibited greater increases in wet future climate scenarios (GCMr90) than the scenario without climate change. In dry scenarios (GCMr10), SOC exhibited smaller increases than the scenario without climate change and in some cases, declining annual SOC by the end of the simulation period (Fig. 4, Supplementary material). Given that 4.5 RCP scenarios were associated with less extreme changes in rainfall (Table 2), modelled changes in SOC using 4.5 RCPs were smaller than changes using 8.5 RCPs. Both models suggest that SOC stocks on the low-rainfall site are more sensitive to a given reduction in rainfall than the high-rainfall site. In dry future climate scenarios, there is a trade-off between stocking rate and soil carbon stocks, particularly on the low-rainfall site. Differences in modelled SOC between hot (GCMt90) and warm scenarios (GCMt90) were typically slight. Although trends were similar with both models, RothC typically simulated greater changes in soil carbon than SGS and showed more variation in SOC response across soil types, particularly on the vertosol

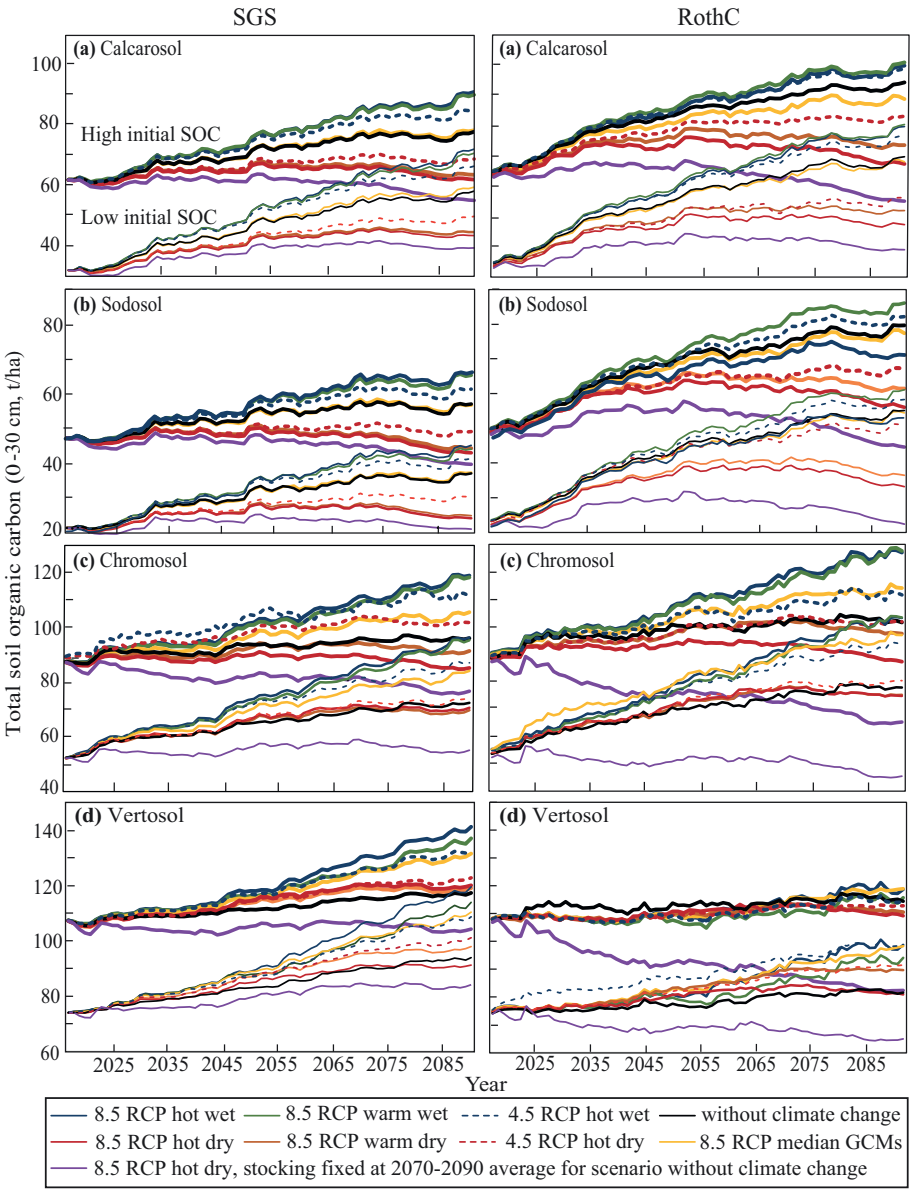

Fig. 4. Change in SOC over the course of the simulation (2017–2090) as predicted by SGS (left) and RothC (right) for low and high initial SOC starting points over several climate and 4 soil type scenarios. Lines orginating in the lower portion (thin) of the graph are scenarios with low initial amounts of carbon and lines originating on the middle or higher portion of the graph (thick) are scenarios with high initial amounts of carbon.

(40% clay). Modelled SOC was more sensitive to overgrazing with RothC than SGS.

4.1. Climate change impacts

In most wet scenarios, the simulated increase in pasture production resulted in increases in SOC and supported increased average 2070–2090 stocking rates, even though increases in rainfall were concentrated in summer when losses from evaporation would be higher. In dry scenarios on the high-rainfall site, SOC stocks were maintained or increased as much as 21 t C/ha (low-carbon Chromosol with RothC) over the simulation period, despite reduced pasture production, but at the cost of declining average 2070–2090 stocking rates. In dry scenarios on the low-rainfall site, particularly those with high initial SOC amounts, soils became carbon sources by the end of the simulation period. Annual reductions in SOC by the end of the simulation in these cases (see Supplementary material) occurred despite the initial soil carbon being set to 50% of the SGS equilibrium for this site and implementing a sustainable stocking management regime.

High emissions scenarios (8.5 RCP) using GCMs that produced the median temperature and rainfall change on the low-rainfall site resulted in similar modelled pasture production, stocking, and SOC as the scenario without climate change. In this case, the impact of a moderate decrease in rainfall in the winter growing season on SOC stocks appears to be mostly compensated for by greater pasture production associated with higher CO_2 concentrations (Fig. 5). Productivity gains from CO_2 offsetting the effects of reduced rainfall have been demonstrated for other sites in south-eastern Australia (Cullen et al., 2009). However, the slight to moderate gains in pasture production did not result in greater average 2070–2090 stocking rates (Fig. 6). Therefore, in these scenarios there are increases in SOC stocks despite reduced rainfall (Fig. 4).

A key factor in this analysis is the large impact of uncertainty in projected rainfall on the modelled response of SOC in south eastern Australia pastures (Fig. 4). Given the large range of uncertainty in the rainfall projections investigated, including differences in the direction of projected change across the scenarios (Table 2), it is consistent that

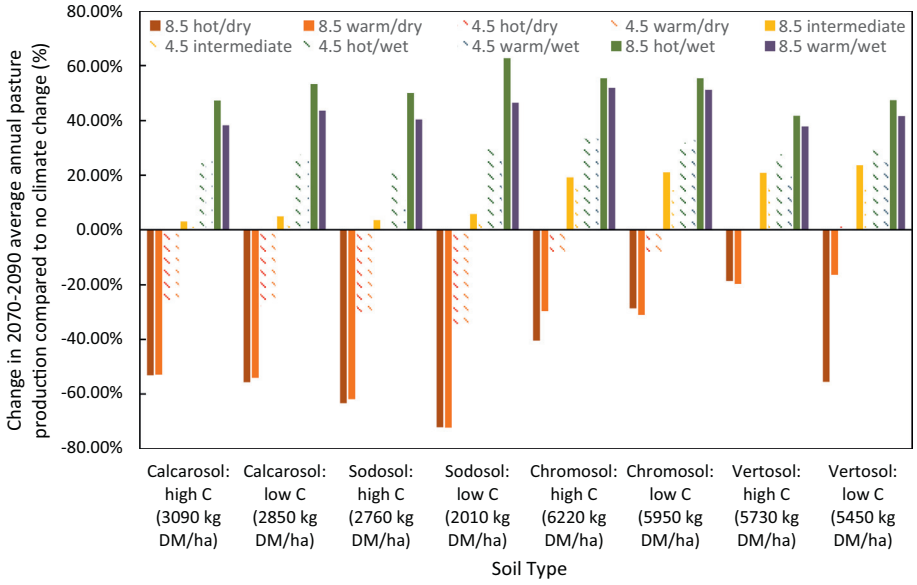

Fig. 5. Percentage difference in 2070–2090 annual pasture production, relative to the scenario without climate change, for all climate and soil scenarios. Values in the parenthesis in the x axis labels are the 2070–2090 annual pasture growth for the scenario without climate change on that soil type.

rainfall would have the largest impact on production and therefore SOC stocks. Rainfall was significantly correlated with, and explained a substantial amount of the variation in, change in SOC over the simulation across scenarios and models (see Supplementary material). The importance of projected rainfall is similar to results for modelling SOC response to climate change using various techniques in New South Wales (Gray and Bishop, 2016), Brazil, Kenya, Jordan, and India (Falloon et al., 2007), North America (Shen et al., 2009), and globally (Gottschalk et al., 2012), and has been shown to be more influential than temperature on some sites (He et al., 2012). These results highlight the need for improved prediction of future rainfall trends in this region and the importance of inclusion of rainfall projections in determining SOC response to climate change at the local or regional level.

The projections included here cover a wide range of uncertainty in future climates and set boundaries on the potential response of soil carbon to climate change, but some scenarios are more likely than others. As noted in the methods, the hot-wet and warm-dry scenarios at the low-rainfall site are particularly unlikely, since drier projections are associated with hotter temperatures in this region (Watterson, 2012). Given the influence of rainfall, these scenarios gave similar results to the more plausible hot-dry and warm-wet scenarios in most soil types.

The increases in rainfall associated with GCMr90 and the large reductions in rainfall associated with using GCMr10 and an 8.5 RCP in this study are also less likely to occur than more moderate declines in rainfall (Timbal et al., 2017). Although the high variability in historic rainfall has made detection of trends difficult, an 11% decline in winter growing season rainfall has been observed since the mid-1990s in south-eastern Australia. Of the last 20 years, 16 have received below average rainfall during the April to October period (Australian Bureau of Meteorology, 2016). There is high confidence in a rainfall decline during winter (June–August; up to −30%) and spring (September–-November; +5% to −45%) in the Hamilton area by 2090 under an 8.5 RCP, with changes in summer and autumn rainfall less certain (Grose et al., 2015). In the Birchip region, there is high confidence that rainfall

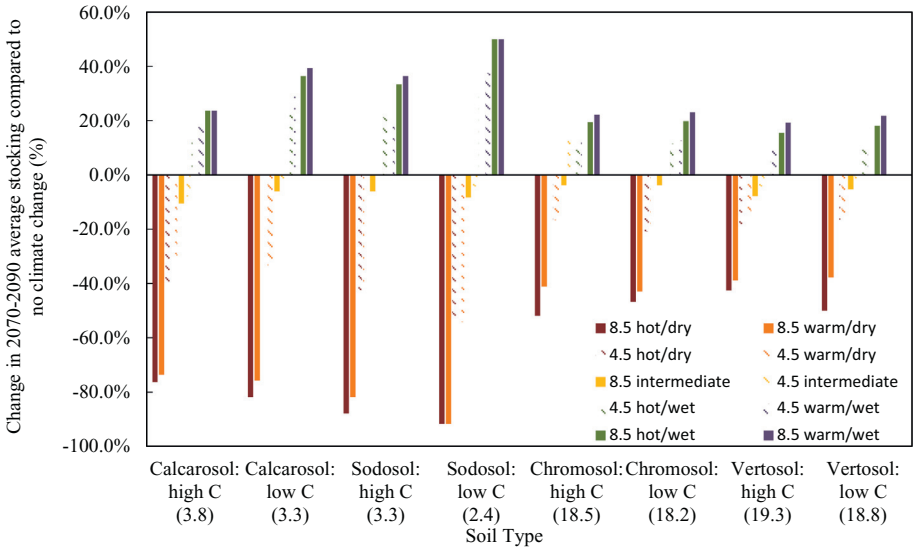

Fig. 6. Percentage difference in average 2070–2090 stocking rate relative to the scenario without climate change for all scenarios. Values in the parenthesis in the x axis labels are the average 2070–2090 stocking rate for the scenario without climate change on that soil type.

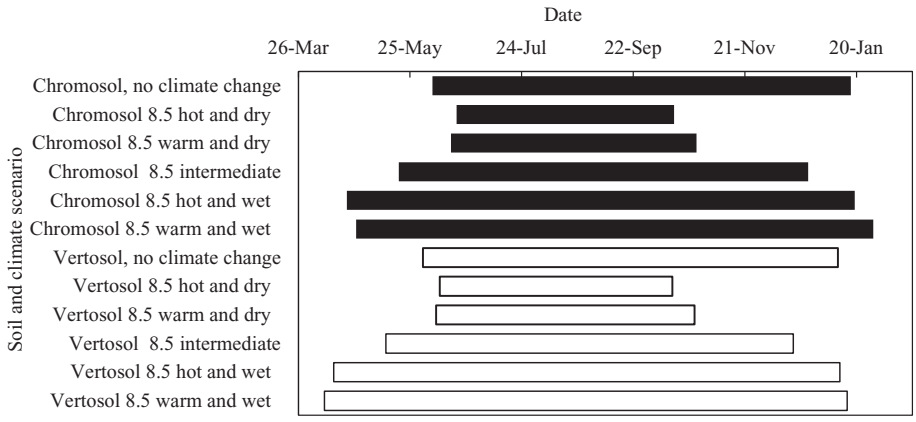

Fig. 7. Median grazing season for 2070–2090 under various high emissions scenarios (8.5 RCP) and the scenario without climate change on the high-rainfall site.

will decline during the cool season from April to October (+5% to −40%) and medium confidence that summer (November–March) rainfall will remain unchanged (Timbal et al., 2015). There is medium confidence in the magnitude of these projections (Grose et al., 2015; Timbal et al., 2015). The wider range of our projections compared to these is likely due to our analysis using a higher spatial resolution (1 km^2). Although there is much uncertainty, the literature suggests projections similar to the median or between the median and dry GCM scenarios in this study are most likely. Although using GCMr10 result in scenarios that are drier than projections with medium confidence (Grose et al., 2015; Timbal et al., 2015), they suggest that management options that currently increase SOC may not reliability do so in potential future climates. They also demonstrate greater vulnerability of livestock production to climate change in more marginal rainfall regions, which has been documented in Australia (Moore and Ghahramani, 2013) and elsewhere (Qiu et al., 2016).

4.2. Stocking management

The other major finding of this analysis is the role of grazing implementation in the simulated response of SOC to climate. Each of the SOC response curves are associated with unique stocking strategies based on the pasture available throughout the simulation; this includes increases in average 2070–2090 stocking rate in wet scenarios and decreases in dry and some median climate scenarios. Previous studies have suggested climate change induced reductions in rainfall would lead to reduced pasture availability in late spring (Cullen et al., 2009), which is reflected in the shortened median grazing season in dry scenarios modelled here (Fig. 7). Climate change induced impacts on above-ground net primary productivity and associated reductions in utilisation rate modelled on several southern Australian sites were associated with major reductions in profitability that increase in severity over time (Moore and Ghahramani, 2013). In this analysis, reductions in average 2070–2090 stocking rate in dry scenarios also led to lower pasture utilisation. If pasture production is adequate, similar pasture utilisation rates across scenarios would be expected. However, in the dry future scenarios pasture production is reduced to the extent that maintaining at least 0.8 t/ha of dry matter leads to a reduction in percentage of total production that animals consume during the grazing period. Lower pasture utilisation means a greater percentage of the pasture is ungrazed and will be transferred into the litter pool and enter the soil C cycle.

Implementing the average 2070–2090 stocking rate from the scenario without climate change in an 8.5 RCP hot and dry scenario resulted in further declines in SOC, over that observed in the hot and dry scenario with grazing influenced by dry matter coverage. On the low-rainfall site, the average 2070–2090 stocking rate was 2 to 4 mature wethers/ha in the scenario without climate change. Implementing these stocking rates every day in a hot and dry scenario resulted in a relatively slow further decline in SOC stocks. A larger impact was observed on the high-rainfall site where the average 2070–2090 stocking rate in the scenario without climate change was 19 mature wethers/ha. The SOC output from RothC was more sensitive to overgrazing than that from SGS, which likely reflects the impacts of having the soil categorized as 'bare' more often in RothC in this fixed grazing scenario.

The modelled stocking management policy allowed SOC to accumulate in many dry scenarios, particularly when SOC contents were initially low, but this was only achieved by reduced average 2070–2090 stocking rates. Although requiring a trade-off between stocking rate and SOC, reducing stocking rate appears to ameliorate SOC losses in a warming and drying climate. Similarly, other studies have found stocking (Nixon et al., 2015) and cropping management (Alvaro-Fuentes et al., 2012; Chen et al., 2015; Farina et al., 2011; Maas et al., 2017; Smith et al., 2010) can influence the extent to which soils become carbon sources or sinks with the progression of climate change.

4.3. Model comparison

Results from RothC and SGS, while not identical, produced similar trends that led to the same general conclusions (Fig. 4, Supplementary material). The predominant role of rainfall and its influence on plant productivity was clear. Increases in SOC under sustainable grazing across the simulation period, particularly at sites with low initial carbon concentrations, were also clear in both models. RothC was consistently more sensitive to overgrazing and predicted greater changes in carbon amounts than SGS. This is most apparent in the sodosol, which likely reflects the restricted rooting depth that was associated with this soil type in SGS (Table 1), but not in RothC. The responses between models differed the most on the vertosol, the soil type with the highest clay content. A given change in either annual rainfall or average minimum winter growing-season temperature had a larger effect on change in SOC with RothC than with SGS on all soil types except the vertosol. Carbon turnover measured in the humic pool of vertosols has been shown to be faster than modelled defaults in RothC (Skjemstad et al., 2001). Given the similarity of responses across soils with clay content ranging from 20% to 40% in SGS and comparative variation in RothC responses, it seems probable that SOC change in RothC is also more responsive to soil clay content than SGS. Correlations between change in SOC over the simulation period and temperature were significant in more scenarios modelled with RothC than with SGS. All the significant correlations between change in SOC and temperature on the low-rainfall site were negative and occurred when modelled with RothC. All of the significant associations between change in SOC and temperature on the high-rainfall site were positive and occurred when using both RothC and SGS (Supplementary material).

4.4. Limitations

Although there are several differences between RothC and SGS's soil carbon model, there are structural sources of variability not incorporated in this analysis. Differences between the two models provide some insight into the impacts of variability in soil carbon modelling on SOC response to climate change. However, higher level structural uncertainties, such as those that could incorporate priming effects (e.g. Guenet et al., 2016; Perveen et al., 2014) and/or microbial or enzymatic activity (Bradford et al., 2016; Georgiou et al., 2015; Srivastava et al., 2017) are not addressed in either model.

This analysis focuses on the top 30 cm of the soil profile. This depth represents the vast majority of the rooting zone for these species (Bolinder et al., 2002; Crush et al., 2005) and would therefore likely contain a greater concentration of SOC than deeper layers (Jobbágy and Jackson, 2000). The surface layers are generally considered to be more responsive to air temperature while clay content and lithology are more influential in deeper layers (Jones and Donnelly, 2004; Muñoz-Rojas et al., 2015). This may explain the long-term increases in subsoil SOC (50–70 cm) observed in modelled cereal pastures in southern Spain, despite declines in shallower layers across several climate scenarios (Lozano-García et al., 2017). However, recent evidence suggests that soil carbon in deeper layers could be similarly sensitive to temperature increases as shallower layers (e.g. Hicks Pries et al., 2017), in which case losses of SOC with long-term increases in temperatures would be greater than found in this analysis.

Although impacts of historic natural variability were investigated with a scenario where the historic time series was randomly shuffled, the potential impacts of extreme events were not incorporated in the modelling. Although a heat wave may not have direct impacts on SOC stocks, these events would likely have negative impacts on plant productivity (Harrison et al., 2016) and thus SOC inputs. These added pressures on SOC stocks are not captured in these results.

Other factors that are not fully captured by this modelling include the impacts of high temperatures on pasture survival, increased water use efficiency with increasing CO_2 concentration, and the role of nitrogen availability. The full impacts of high temperature on pasture mortality are not incorporated into SGS; thus, are likely underestimated. Increased water use efficiency with increasing CO_2 concentrations can result in increased soil moisture due to reduced plant transpiration (Leakey et al., 2009), but this relationship is not included in SGS. Increased soil moisture can both increase soil respiration, a potential negative impact on SOC (Pendall et al., 2003), and improve plant productivity, a potential positive impact on SOC. The net effect in this case is uncertain, but likely to be small relative to rainfall. Both sites were modelled with a legume included in the pasture, which reduced the likelihood of plant growth being limited by nitrogen. The presence of a legume also leads to lower C:N ratios, and thus increased turnover of organic matter.

4.5. Implications

These findings have important implications for climate change policy and long-term farm planning in regions like south eastern Australia. The large uncertainty in future rainfall projections leads to uncertainties in the potential for carbon accumulation in the future. In addition to reducing future uncertainty through improved rainfall projections, further research quantifying the potential of a suite of adaptation options is needed. Addition of C_4 grasses (Bell et al., 2012), deeper-rooted grasses (Kalaugher et al., 2017) and lucerne (*Medicago sativa*) to pastures and additions of nutrients, such as phosphorus (Ghahramani and Moore, 2013), have shown potential to alleviate climate change impacts on grazing systems in the short or medium term. However, few adaptation options have been shown to offset losses associated with high-emissions scenarios over long timeframes (Ghahramani and Moore, 2013).

Concurrent mitigation efforts to limit climate change impacts to the range in which adaptation can be effective are critical. Modelled impacts on pasture production, stocking and the ranges of possible SOC responses associated with 4.5 RCPs were substantially less than the impacts of the 8.5 RCPs. Reduced impacts of lower emissions scenarios have been demonstrated elsewhere (Maas et al., 2017; Monier et al., 2016; Tebaldi and Lobell, 2015).

Although the modelling results of this study suggest in the near to medium term it is reasonable to aim for SOC accumulation in areas where SOC is low and maintaining SOC in areas where it is high, the variability in rainfall projections for south eastern Australia adds more risk and uncertainty for farmers considering trading in soil carbon offsets. Of pasture areas in western Victoria, 23.5% have average annual rainfall within 1 SD of Birchip's rainfall. These areas, located in north western Victoria (Fig. 2), are likely to struggle to maintain SOC stocks and current stocking rates, if drier projections prove accurate. The potential need to substantially reduce stocking rates to meet carbon maintenance obligations, along with costs associated with monitoring and verification, would likely make soil carbon trading unviable. However, the productivity benefits of increased SOC now and in a warmer climate (Jarvis et al., 2011; Joyce et al., 2013; Meyer et al., 2015) would benefit farmers and may achieve some mitigation, without the risks associated with having a carbon maintenance obligation when they do not control the overriding influence – future rainfall.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.08.010.

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